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CONTAINMENT VESSEL LEAK-RATE TESTING - EXPERIENCES AT THE NASA PLUM BROOK REACTOR

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SUMMARY

The leak rate of the Plum Brook Reactor (PBR) containment vessel has been measured by two methods - the absolute-temperature-pressure method and the reference-system method. Both methods are described, and the equations for leakage in each method are investigated in detail. The results of three leak-rate tests in which both methods were employed simultaneously show substantial agreement. In one of these tests the accuracy of results was verified experimentally by employing a known leak rate. For PBR test conditions the absolute method was found to offer greater overall simplicity than the reference-system method. However, the reference-system method consistently yielded results having less scatter than the absolute-method results and proved to be an accurate and satisfactory method of measurement.

INTRODUCTION

In order to ensure the safety of the general public, the operation of a nuclear reactor is subjected to comparatively extreme and rigid safeguards against an accidental release of fission products resulting from an uncontrolled nuclear accident. One of the structural deterrents to such a release is a virtually leak-tight containment vessel that completely surrounds the reactor core and pressure tank (fig. 1). The tightness requirements of a containment vessel, which are generally quite extreme, are established from considerations of:

(1) The maximum credible nuclear accident and the resultant fission product concentration in the containment vessel

(2) Meteorology as related to the dispersion of fission products

(3) Permissible radiation exposure to the general public.

As an example of these tightness requirements the 520,000 cu ft Plum Brook Reactor (PBR) containment vessel is subjected to a maximum allowable leak rate of 115 standard cu ft/day at an overpressure of 0.3 lb/sq in. gage. To ensure that these requirements are continually satisfied, it is necessary to conduct periodic or, ideally, continuous leak-rate tests.

The leak-rate testing of a containment vessel, which is quite simple in principle, is actually quite difficult and time consuming in practice. Since a test involves measuring an extremely small leak rate, the initial problem is one of determining the extent to which a number of ordinarily insignificant variables may affect the accuracy of results. As an example, for PBR conditions a 1° F change in vessel air temperature could completely mask a full day of leakage at the maximum allowable leak rate; therefore, it is essential that the average temperature of the 520,000 cu ft volume be measured with great accuracy and precision.

Because of such typical difficulties it is not unusual that at various reactor sites testing periods on the order of a week have sometimes been required before the leak rate was determined with sufficient accuracy. Hence, an accurate testing method requiring a short testing period is desirable for reasons of economy alone.

The two testing methods most commonly employed are the absolute-temperature-pressure method and the reference-system method. Both have had varying degrees of success.

In the absolute method the leakage is determined directly from measurements of the absolute temperature and pressure together with the equation of state for a perfect gas. This method has been successfully employed by Heineman and Fromm (ref. 1) in testing the Experimental Boiling Water Reactor (EBWR) vessel. In their initial test a period of 8 days was required before the leak rate was determined to the desired accuracy (ref. 2). In subsequent tests they were able to reduce the testing period to a day or two principally because an absolute manometer, which could be read to 0.001 in. Hg, was employed.

The reference-system method was first proposed by Untermeyer and Layton (ref. 3) and used by them to test the Vallecitos Boiling Water Reactor (VBWR) vessel. In this method the leakage is indicated by the pressure differential between the vessel being tested and a leak-tight system of tubing distributed within the vessel where both are at the same overpressure initially. The principal attraction of this method is its temperature compensation, which permits increased accuracy because only pressure measurements, obtainable with great accuracy and precision, are required. However, it may be questioned as to whether or not a reference system is truly temperature compensating. The wall of the reference system in itself offers a resistance to the passage of heat. Hence, during a diurnal temperature variation, there will be only two times when the reference system and containment vessel temperatures are identical because of an unavoidable thermal time lag. If a reference system is not temperature compensating, it would then be necessary to make direct temperature measurements in this method also as in the absolute method. Use of the reference-system method would then be superfluous.

Despite such conceivable shortcomings, the successful use of the reference-system method has been reported in references 3 and 4. In reference 4 it was reported that the Dresden containment sphere was tested in a 30-hr period and that the absolute method would have required a testing period of 1 week in order to have been of comparable accuracy. In tests of a volume of much smaller magnitude (14,500 cu ft) at the Lewis Research Center's zero-power research reactor both methods were employed. The two methods yielded closely agreeing results, but the data from the reference-system method was more consistent and convenient (unpublished NASA test data).

In contrast to the foregoing experiences, however, Jaroschek and Weippert (ref. 5), after testing the DIDO and MERLIN containment vessels of the atomic research installation of the Landes Nordheim-Wesfalen at Julich, Germany in which both methods were employed, recommended the use of the absolute method in all future tests. They concluded that temperature measurements were also required in the reference-system method, which accordingly did not offer any improvement in the accuracy of results. Their measurements with the reference-system method could not be evaluated and compared with the absolute-method results because the reference system did not show sufficient tightness.

For one planning a leak-rate test, the conflicting experiences reported make the choice of a testing method somewhat problematical. Probably the best introduction to the problems involved in various testing methods may be found in reference 2. Also, a brief survey of testing methods may be found in reference 6.

In the first three PBR tests, the reference-system method was employed. In addition, however, the measurements of the vessel air temperature, which were originally made primarily for general monitoring purposes, were also used to determine the leak rate by the absolute method. Thus, the results of both methods have been compared in order to aid test engineers in the choice of a testing method. In addition, the expressions for leakage in both methods have been investigated in detail in order to establish the validity of some of the objections to the reference-system method.

The purposes of this paper are:

(1) To describe, analyze, and compare the methods used to measure the PBR containment vessel leak rate

(2) To present some of the experiences encountered in testing the PBR containment vessel

It should be added that the major part of this report is devoted to the reference-system method of measurement. The same treatment was not believed necessary in the case of the absolute method, since the measuring methods and instruments involved are quite familiar and straightforward.

SYMBOLS

P pressure

ΔP difference in pressure between containment vessel and reference system

R gas constant

T temperature

V volume

W weight of air

τ time

Subscripts:

ind indicated or measured value

r reference-system properties

s indications of any system of temperature sensors

v containment vessel properties

0 time at which pressurization is completed and reference system is isolated from containment vessel

1 time of first measurements

2 time of later measurements

Discussion of Equations Employed

In the absolute method, where a perfect gas is assumed and the equation of state is employed, the weight of air within the pressurized vessel at the initiation of the test is

$$W_{v,1} = \frac{P_{v,1}V_{v,1}}{RT_{v,1}} \tag{1}$$

At any later time, the weight of air is

$$W_{v,2} = \frac{P_{v,2}V_{v,2}}{RT_{v,2}} \tag{2}$$

If a constant vessel volume is assumed, the fractional loss of contained air from equations (1) and (2) is

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = 1 - \frac{P_{v,2}}{P_{v,1}}\left(\frac{T_{v,1}}{T_{v,2}}\right) \tag{3}$$

In an actual test a system of temperature sensors is required to measure $T_{v,1}$ and $T_{v,2}$. Generally the measured average temperature will not be identical to the true average temperature because of instrument inaccuracies, personal error, and inadequate sampling. Hence, making a distinction between the indicated and actual average temperature, the indicated leakage is

$$\left(\frac{W_{v,1} - W_{v,2}}{W_{v,1}}\right)_{ind} = 1 - \frac{P_{v,2}}{P_{v,1}}\,\frac{T_{s,1}}{T_{s,2}} \tag{4}$$

The actual fractional weight loss may be obtained from equation (4) by multiplying both $T_{s,1}$ and $T_{s,2}$ by appropriate temperature ratios as follows:

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = 1 - \frac{P_{v,2}}{P_{v,1}}\,\frac{T_{s,1}}{T_{s,2}}\left(\frac{T_{v,1}}{T_{s,1}}\right)\left(\frac{T_{s,2}}{T_{v,2}}\right) \tag{5}$$

which is identical to equation (3). In an actual test T_v is not known but is estimated by T_s, and hence equation (5), the exact expression for leakage, is not usable. To be in a usable form, two temperature ratios must be neglected, resulting in equation (4), the indicated expression for leakage. The foregoing distinction between indicated and actual quantities is made primarily for a later discussion and comparison of the absolute and reference-system methods.

In the reference-system method, consider that the vessel and reference system have been brought to the testing pressure. The reference system is then closed at time τ_0, and the required periodic measurements are begun. Since a period of time has elapsed between closing the reference system and taking the first set of readings, the difference in the pressures of the reference system and the containment vessel is

$$P_{r,1} - P_{v,1} = \frac{W_{r,1}R_{r,1}T_{r,1}}{V_{r,1}} - \frac{W_{v,1}R_{v,1}T_{v,1}}{V_{v,1}} = \Delta P_1 \qquad (6)$$

At any later time,

$$P_{r,2} - P_{v,2} = \frac{W_{r,2}R_{r,2}T_{r,2}}{V_{r,2}} - \frac{W_{v,2}R_{v,2}T_{v,2}}{V_{v,2}} = \Delta P_2 \qquad (7)$$

It is assumed that

(1) R is a constant throughout the test and is the same in both the reference system and the containment vessel.

(2) The density of air within the reference system is constant.

(3) The reference-system and containment vessel volumes are constant.

Then solving for the weight of air in the vessel at both times results in

$$W_{v,1} = \frac{V_v}{T_{v,1}}\left(\frac{W_r}{V_r} T_{r,1} - \frac{\Delta P_1}{R}\right) \qquad (8)$$

$$W_{v,2} = \frac{V_v}{T_{v,2}}\left(\frac{W_r}{V_r} T_{r,2} - \frac{\Delta P_2}{R}\right) \qquad (9)$$

From equations (8) and (9) it can be determined that

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = \frac{W_r V_v}{V_r W_{v,1}}\left(\frac{T_{r,1}}{T_{v,1}} - \frac{T_{r,2}}{T_{v,2}}\right) + \frac{V_v}{RW_{v,1}}\left(\frac{\Delta P_2}{T_{v,2}} - \frac{\Delta P_1}{T_{v,1}}\right) \qquad (10)$$

Using the equation of state to modify equation (10) produces the final expression for the percent loss as given in reference 2

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = \frac{P_{r,1}}{P_{v,1}} \frac{T_{v,1}}{T_{r,1}} \left(\frac{T_{r,1}}{T_{v,2}} - \frac{T_{r,2}}{T_{v,2}} \right) + \frac{1}{P_{v,1}} \left(\frac{T_{v,1}}{T_{v,2}} \Delta P_2 - \Delta P_1 \right) \qquad (11)$$

Equation (11) suggests that, even if the reference-system temperature were equal to the vessel air temperature at all times (i.e., $T_{r,1} = T_{v,1}$ and $T_{r,2} = T_{v,2}$), it would still be necessary to measure the vessel air temperature continuously. If the vessel air temperature measurements are required, it would be pointless to use the reference-system method, which supposedly offers the advantage of eliminating direct temperature measurements. However, without making any additional assumptions, equation (11) may be rearranged into the more meaningful and convenient form

$$\frac{W_{v,1} - W_{v,2}}{W_{v,1}} = 1 - \frac{P_{v,2}}{P_{v,1}} \frac{(P_{v,1} + \Delta P_1)}{(P_{v,2} + \Delta P_2)} \left(\frac{T_{v,1}}{T_{r,1}} \right) \left(\frac{T_{r,2}}{T_{v,2}} \right) \qquad (12)$$

From this equation it would still seem that temperature measurements must be made; however, as in equation (5) a distinction between the indicated and actual temperatures (implicit in eqs. (6) and (7)) has also been made here. Furthermore, from the perfect gas law it may be shown that $(P_{v,1} + \Delta P_1)/(P_{v,2} + \Delta P_2) = T_{r,1}/T_{r,2}$. If this is substituted into equation (12) and compared to equation (5), the two equations are seen to be equivalent; the only difference is that equation (5) applies to any system of temperature sensors, whereas equation (12) applies to a particular type of temperature sensor, a reference system, which may be thought of as a gas thermometer. In practice it is not possible to use equation (12) because the true average vessel temperature T_v is not determinable on account of sampling limitations alone. Hence, the two temperature ratios must be neglected, and the indicated values of temperature $(P_V + \Delta P)$, are used to determine an indicated value of the fractional weight loss according to the expression

$$\left(\frac{W_{V,1} - W_{V,2}}{W_{V,1}}\right)_{ind} = 1 - \frac{P_{V,2}}{P_{V,1}} \frac{(P_{V,1} + \Delta P_1)}{(P_{V,2} + \Delta P_2)} \tag{13}$$

Lest neglecting these temperature ratios be viewed as a fundamental shortcoming of the reference-system method, it should be noted that two temperature ratios must likewise be neglected in the absolute method (see eqs. (5) and (4)); in both instances these ratios result from distinguishing between the indicated and actual temperatures. In both cases the scatter in the indicated fractional loss results would be indicative of the accuracy with which the actual average temperature is measured.

PRECISION AND ACCURACY OF RESULTS

In the case of two temperature measuring systems that sample essentially the same portions of a volume, the comparative scatter of results for a large number of measurements will be influenced by the precision attainable in each method. Hence, in the present case, it would appear that the comparative scatter of data depends upon whether the "temperature" sensed by the reference system $(P_V + \Delta P)$, may be measured with greater precision than the direct temperature measurement T_V, in this case obtained by thermocouples. However, the scatter of data is dependent upon another condition, which may be seen by rearranging equations (5) and (12) to the forms

$$\left(\frac{W_{v,1} - W_{v,2}}{W_{v,1}}\right)_{ind} = 1 - \frac{T_{v,1}}{P_{v,1}} \frac{P_{v,2}}{T_{v,2}} \tag{14}$$

and

$$\left(\frac{W_{v,1} - W_{v,2}}{W_{v,1}}\right)_{ind} = 1 - \frac{P_{v,1} + \Delta P_1}{P_{v,1}} \frac{P_{v,2}}{P_{v,2} + \Delta P_2} \tag{15}$$

Any errors present in the measurements at τ_1 become a source of fixed error in the results of both methods. Since a leak rate is being measured, a fixed error is of little consequence. For the measurements by the reference-system method at τ_2, an error in $P_{v,2}$ will result in the same error being introduced into the "temperature" measurements $(P_{v,2} + \Delta P_2)$. The ratio $P_{v,2}/(P_{v,2} + \Delta P_2)$, however, will not be changed significantly. A 1-percent error in $P_{v,2}$ will result in an error of only 0.01 percent in the ratio $P_{v,2}/(P_{v,2} + \Delta P_2)$. In the reference-system method, then, the temperature and pressure measurements are, in a sense, coupled, resulting in the virtual cancellation of pressure measurement errors.

In the absolute method, an error in $P_{v,2}$ is quite independent of the measurement of $T_{v,2}$. Thus, even if the temperature measurements were extremely precise and accurate, any pressure measurement errors would produce scatter in the percent loss results. In this case a 1-percent error in $P_{v,2}$ will also result in a 1-percent error in the ratio $P_{v,2}/T_{v,2}$.

Hence the comparative scatter in the fractional weight loss results is not only attributable to the relative precision and accuracy of temperature measurements in each method but is partly a consequence of the interdependence of the "temperature" and pressure measurements in the reference-system method.

In comparing the accuracy of the two methods the effects of diurnal temperature variations on each set of temperature indications should be considered. During diurnal temperature variations, the small mass of a thermocouple enables it to respond virtually instantly to such changes. A reference system is quite massive by comparison, however, and, despite the long period of daily temperature cycles, the thermal time response may be prohibitively large if it is considered that only a 1° F temperature error could completely mask the allowable leak rate.

Because of the uncertainty of thermal time-lag errors, the magnitude of the temperature-time lag of various sized systems (2,12, and 24 in. diam.) was investigated analytically (ref. 7). The reference system was considered as an infinitely long "solid" cylinder of air in which heat transfer occurs only by conduction. The metallic (copper) wall was replaced by an equal layer of air in order to provide conservative results. For a sinusoidally varying surface temperature with a period of 8 hr and an amplitude of 8° F, the variation of centerline temperature was determined using a solution from reference 8. The maximum error due to a thermal time lag in the 2-in.-diameter system was calculated to be 1.4 percent, while for 12- and 24-in.-diameter systems the maximum errors are 90 and 280 percent, respectively. These estimates are probably overly conservative, however. Practically, a system of about 1/2-in. diameter would be much more convenient to employ, and the thermal time-lag errors could be considered negligible. With such a system it may be concluded that the accuracy of average temperature measurements would more likely be limited by the inability to adequately sample the vessel volume.

At the other extreme it is conceivable that the extreme sensitivity of a system of thermocouples could also be a source of error. A fast response instrument would react to virtually every passing air mass and hence give nonrepresentative indications. To prevent such errors the thermocouples could perhaps be imbedded in small copper blocks, which would damp out spurious temperature fluctuations.

In comparing the two methods of temperature measurement, it is obvious that the reference system affords the advantage of continuous spatial sampling in contrast with the point samplings obtained from a system of thermocouples. In the first three leak-rate tests conducted at the PBR in which both methods were employed simultaneously the spatial orientation of both temperature measuring systems was essentially the same. Hence, the comparative scatter of data should be indicative of the relative overall precision of each measuring method.

Because of the typically large containment vessel volumes it is desirable to have some certainty that the leak-rate indication is an accurate one, rather than merely a reflection of localized conditions. In PBR tests this was accomplished by superimposing a known leak rate upon the existing vessel leak rate during part of the test period. If the measuring system is accurate, this will produce a corresponding change of slope in the indicated weight loss against time curve.

Description of Containment Vessel

The PBR core and its pressure tank are housed within a cylindrical steel containment vessel having an elliptical top as shown in figure 1. The containment vessel has an inner diameter of 100 ft, and its height above grade is approximately 55 ft. The wall extends downward to the shielding pool floor level, 25 ft below grade, and then continues on as the containment vessel bottom. The shielding pool, which surrounds the reactor pressure tank, is approximately 70 ft in diameter and is divided into quadrants (fig. 2). Surrounding the pool and inside the containment tank is an annular space 13 ft wide and 25 ft deep. Part of the annulus is occupied by a canal. The canal and three of the quadrants are normally filled with water to a depth of 25 ft, and the total exposed water surface area in this case is 3860 ~~4670~~ sq ft.

The containment vessel is surrounded by the reactor building to a height of 27 ft above grade. The reactor building houses the reactor control room, offices, shop and personnel facilities, and experimental areas. Hence the reactor building serves as an insulating mass, which helps to maintain a constant room temperature within the containment vessel. The containment vessel dome is also covered with 2 in. of fiber glass insulation. The wall and dome structure is 3/4-in. plate, while the bottom disk is welded 3/8-in. plate. Access to the vessel is gained through two sets of air-lock doors and a truck door.

Penetrations of the vessel fall into three categories - welded, potted, and gasketed. Service lines are welded, electrical lines are potted, and all doors are gasketed. Since potted and gasketed seals are most susceptible to leakage, these two types are employed in a double seal arrangement (fig. 3) with the volume between being maintained under a vacuum. The potting compound which has been most satisfactory to data is Minnesota Mining and Manufacturing's type EC 801. The vacuum system returns any collected leakage to the containment vessel.

Procedure and Apparatus

In the first three tests both the absolute and reference-system methods were employed. In the first test, two independent reference systems were employed (figs. 4 and 5). One system consisted of a 20-ft length of 2-in.-diameter copper tubing, located at the vessel centerline, which was connected to an inclined manometer immediately outside the vessel by means of an 80-ft length of 1/4-in.-diameter copper tubing. The second system consisted of a 60-ft length of 1-in.-diameter copper tubing, which was connected to a micromanometer by means of a 20-ft length of 1/4-in.-diameter copper tubing. Two systems were employed in order to determine whether or not significant temperature gradients were present in the vessel interior. Absolute temperature measurements were obtained from a single resistance thermometer located at the approximate geometric center of the vessel and suspended from the 20-ton crane.

In the second and third tests only the 2-in.-diameter system was employed for the reference-system measurements. Temperature measurements for the absolute method were obtained from the resistance thermometer and three iron-constantan thermocouples soldered to the outer surface of the 2-in.-diameter tube and spaced as shown in figure 4.

Absolute pressure measurements were obtained by combining the readings of a 10-ft water manometer measuring the vessel gage pressure and a standard precision barometer.

Water vapor pressure measurements were made at two positions along the vessel centerline.

A description of the instruments employed is as follows:

(1) One micromanometer and one inclined water manometer for measuring the pressure differentials between the containment vessel and the 1- and 2-in.-diameter reference systems, respectively; least division, 0.01 in. (Both the micromanometer and inclined manometer were filled with a fluid that had a saturated vapor pressure of 0.00005 in. of water at 77° F to eliminate the necessity of making vapor pressure corrections in the reference system.)

(2) One 10-ft water manometer for measuring the pressure differential between the containment vessel and the atmosphere; least division, 0.1 in.

(3) One standard precision mercury barometer; least division, 0.01 in.

(4) One gas flowmeter for metering a controlled leak; range, 0 to 165 cu ft/hr; least division, 0.1 cu ft.

(5) Two Foxboro (Dewcel) dewpoint indicators for measuring the partial pressure of water vapor in the vessel atmosphere; least count, ~0.1° F dewpoint temperature.

(6) One potentiometer for Dewcel and thermocouple measurements; least division, 0.001 mv.

(7) One Mueller bridge for the resistance thermometer measurements; least division, 0.001 Ω.

PROCEDURE

All PBR tests are accelerated: that is, the vessel overpressure is 4 lb/sq in. gage rather than the 0.3 lb/sq in. gage calculated for the maximum credible accident. At the higher overpressure the allowable leak rate is 1530 standard cu ft/day or ~0.27 percent of the initial total weight of contained air per day.

A typical test procedure is as follows: The reference system (includes all tubing, valves, and manometer connections) is first thoroughly tested for leaks with a helium mass-spectrometer. This check may be conducted with the system in the vessel but not in its test position. The reference system is next subjected to an additional test by pressurizing to 50 lb/sq in. gage for a 12-hr period, in which time no measurable leakage is permissible. During the latter test, all remaining instrumentation is installed and checked out. When proof of the integrity of the reference system has been established, the containment vessel is isolated simply by energizing the containment seal button in the reactor control room, which automatically closes valves in all those lines which could possibly provide a path for any leakage from the containment vessel.

The vessel is then pressurized to 1 lb/sq in. gage by two 500 hp Ingersol-Rand compressors in a few minutes. Valves 2, 3, 5, and 6 (fig. 5) are left open to permit the simultaneous pressurization of the reference system and containment vessel. The vessel is then given an audiovisual check for large leaks. After eliminating any leaks so found, the vessel is further pressurized to 4 lb/sq in. gage. The reference system is then isolated by closing valves 2 and 3, and a thorough soap-bubble check is made of all likely points of leakage. Throughout this check the differential pressure in the inclined manometer is monitored. As soon as the pressure-time data appear to indicate a leak rate significantly lower than the allowable, the recording of data is begun.

Data are taken at 1-hr intervals for a period of 48 hr. During the last 16 hr of the test, valves 1 and 4 are opened and adjusted to permit air to be bled from the vessel through a gas flowmeter at a rate roughly equal to the allowable.

Throughout the test, four air conditioning units are in operation so as to maintain a constant air temperature and relative humidity. Circulation of the vessel air is effected by these units, which are spaced equally around the vessel wall. Each unit circulates air upward along the wall and across the dome toward the center of the vessel where mixing occurs.

CORRECTION FACTORS

In PBR tests it was found necessary to measure and correct for

(a) Decrease in reference-system pressure caused by changing water level in inclined manometer (volume change)

(b) Changing water vapor pressure in containment vessel air

Also, since the air conditioning units are pneumatically controlled, air is normally introduced into the vessel intermittently. During a test, these units are converted to operate off of a pressurized bottled nitrogen supply. The change in weight of the nitrogen bottle over the test period permits an appropriate correction to be applied to the indicated leak rate.

RESULTS

The results of three tests are shown in figures 6, 7, and 8. The "best fit" leak rates were obtained by the method of least squares. The limits of error were estimated by assuming a gaussian distribution of the fractional weight loss data and calculating the standard deviation by standard statistical methods.

In the first test (fig. 6), the results of the two reference systems are virtually the same. Since the spatial orientation of the systems was different, it was concluded that the temperature gradients in the vessel interior were not significant; thus, a single system was used in subsequent tests. The results of both methods are in agreement. Also, the scatter in the reference-system results is significantly less than that in the absolute-method results.

In the second test (fig. 7), both methods again agree but not as well as in the first test. The scatter of results is again smaller in the reference-system method.

In the third test (fig. 8), it was established that the resistance thermometer readings were erroneous throughout the test period, which prevented a leak-rate determination from these temperature measurements. A number of thermocouple measurements were suspected of being inaccurate; since this could not be proven with certainty, the fractional weight loss results were plotted but were not included in the least-squares or error calculations.

The third test differs significantly from the first two in that a controlled leak period was incorporated to check the accuracy of results. The controlled leak rate introduced was measured to be 0.226 percent per day. Subtracting this amount from the indications of the previous period reveals the general agreement and accuracy of both methods. The scatter of results was again significantly less in the reference-system method.

Considering the three tests together, it appears that the only time undue scatter occurred was during comparatively rapid temperature changes. It also appears that any temperature changes were accompanied by an increase in the scatter of results. Since it has been shown by a thermal time-lag analysis that the reference system is virtually free from thermal time-lag inaccuracies, such scatter may be attributed to the concurrence of the following:

(1) The incomplete sampling of the vessel atmosphere

(2) The spatial temperature variation of the vessel air

The foregoing conclusions also apply to the absolute-method results. In addition, since the scatter of results was never so great as to make the trend of data unrecognizable or unmeaningful, the accuracy of the average temperature and water vapor pressure measurements was indicated to some extent. Although the accuracy of both methods was experimentally verified by means of the known leak-rate method, the scatter of future test results might be reduced by increasing the number of dewpoint sensors employed.

Experiences have shown that absolute method offers a greater overall simplicity than the reference-system method does; the problems associated with the preparation and installation of a few thermocouples are much smaller than those associated with the preparation of a reference system. However, the reference-system method consistently yielded results having less scatter than the absolute-method results did and proved to be an accurate and satisfactory method of measurement.

At higher testing pressures it is unlikely that the vessel gage pressure may be measured to 0.05 in. WATER as in these tests. In accordance with the observations in the section Precision and Accuracy of Results, a larger error in the pressure measurement would be of much less consequence in the reference-system method. To counteract the increased error in the absolute-method results, it would be necessary to increase the accuracy of temperature measurements, perhaps by increased sampling. Hence, at higher testing pressures the maintenance of the same relative accuracy in the two methods would probably necessitate increased complication in the absolute method.

Various Testing Experiences

In the first test all leak searches were conducted outside the vessel. In subsequent tests, many more leaks could be found by entering the vessel through the air locks, while at the testing pressure, and listening for leakage. When as many systems as possible were shut down, the noise level within the vessel was low enough to allow even minute leaks to be heard. The largest leaks found were through valves and around electrical cable penetrations. In the latter, about half of the leaks were between the cable sheath and the potting in the penetration seal; the other half occurred along the inside of the cable because of faulty end potting on cut cable sheaths. A quick setting rubber cement was used for repair. All of these leaks were easily fixed since the air pressure forced the cement into the leak with a self-caulking action. Door seals were observed to leak only slightly. Only two faulty pipe penetrations were found.

SUMMARY OF RESULTS AND CONCLUSIONS

Reviewing both the experimental and analytical aspects of the PBR leak-rate testing program, some of the more significant results and conclusions are:

1. Thermal time-lag effects in the reference-system method may be made insignificant by making the reference system of sufficiently small diameter tubing ($\approx$1/2 in.). Consequently, the accuracy with which such a reference

system senses the average vessel air temperature is likely to be limited by sampling errors.

2. In all three tests conducted to date, the leak-rate determinations of both the absolute and reference-system methods were in substantial agreement.

3. In all cases the reference-system method consistently yielded results having less scatter than those of the absolute method.

4. For PBR conditions the absolute method offers the advantage of greater overall simplicity, although the reference-system method proved to be an accurate and satisfactory method of measurement. Also, at higher testing pressures the relative simplicity probably decreases.

5. The accuracy of the leak-rate results may be conveniently illustrated experimentally by superimposing a known leak rate upon the vessel leak rate during part of the test period.

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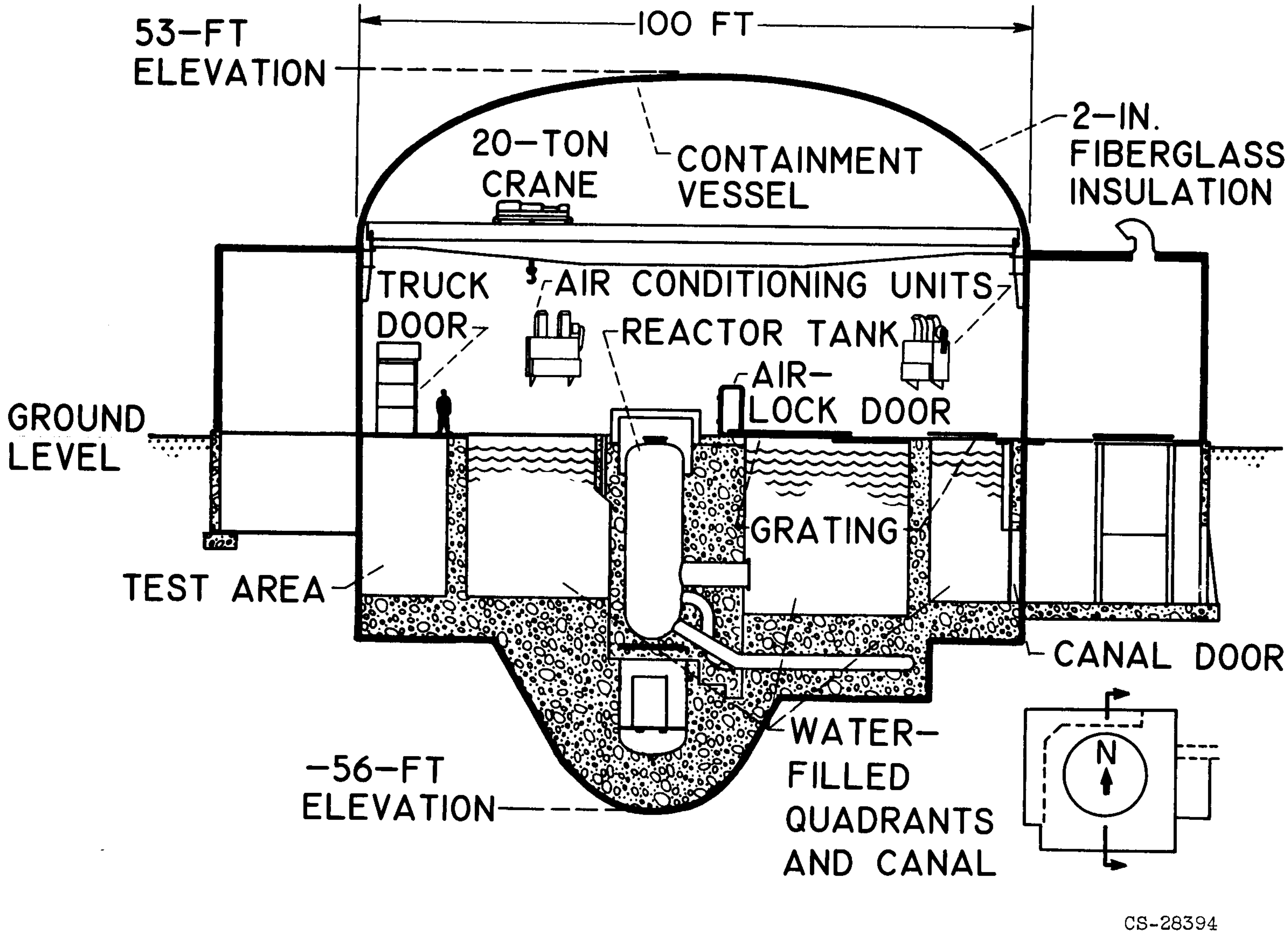

Figure 1. - Vertical section of reactor building.

Figure 2. - Containment vessel interior.

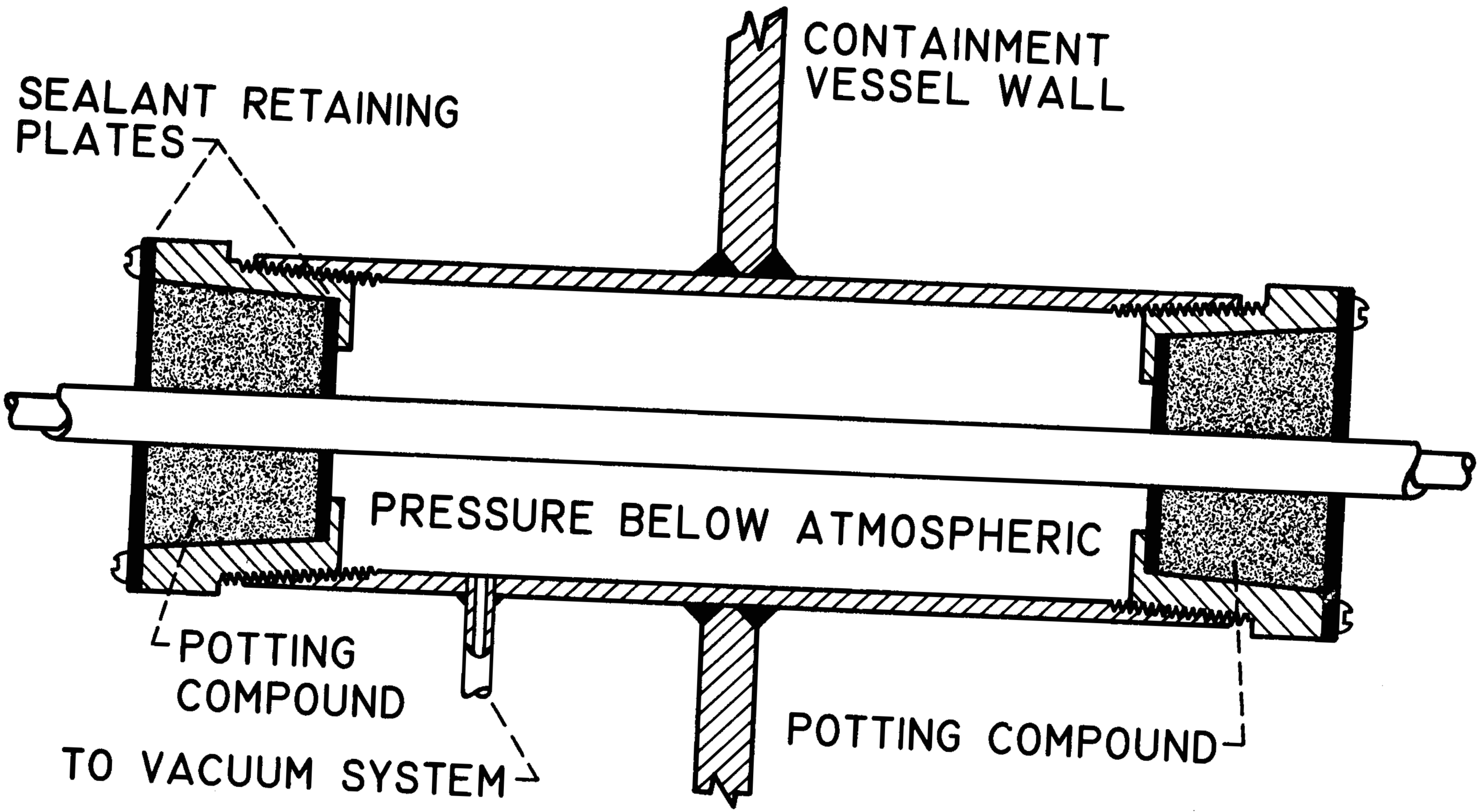

Figure 3. - Typical wire or cable penetration.

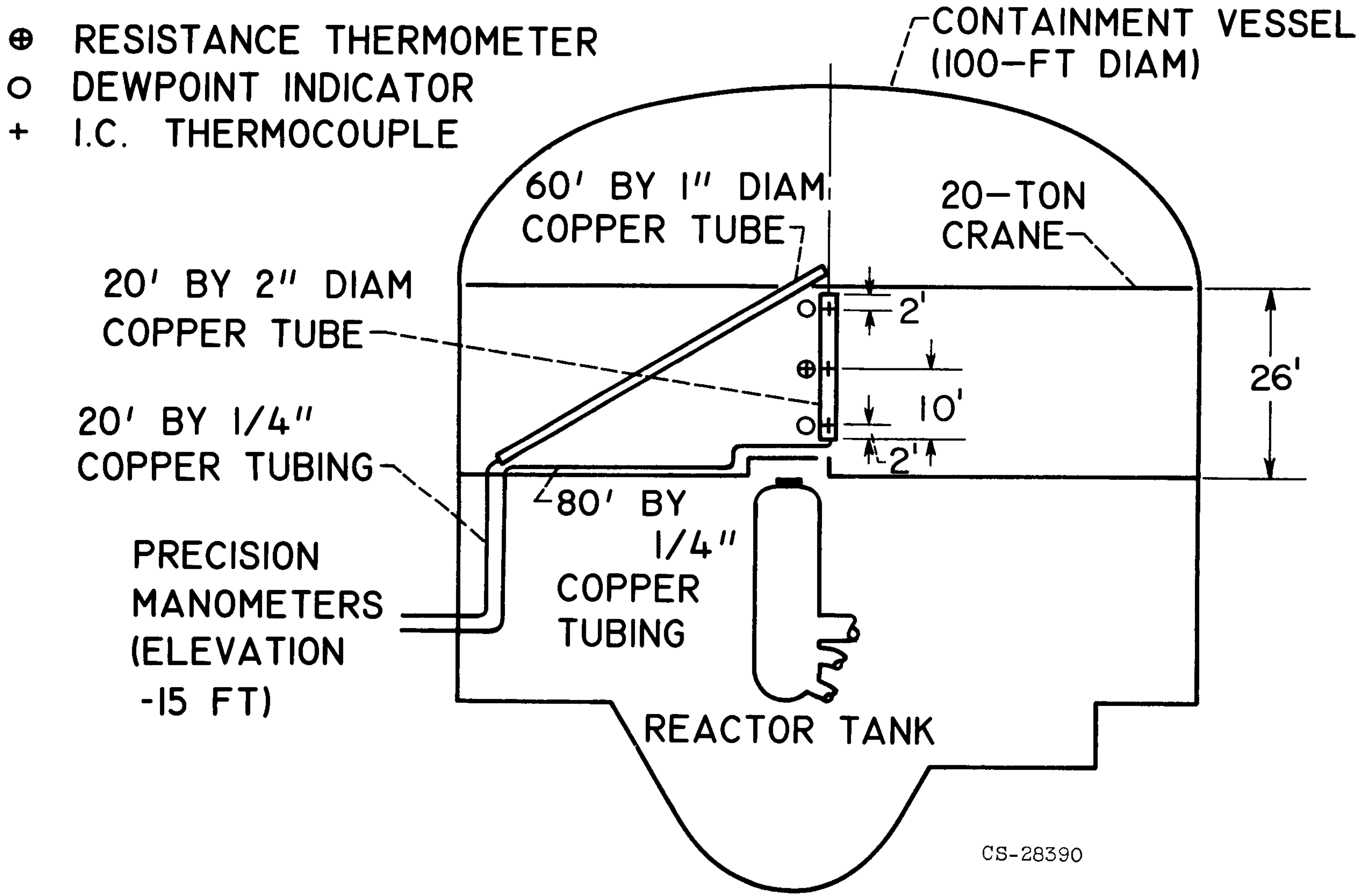

Figure 4. - Location of instruments.

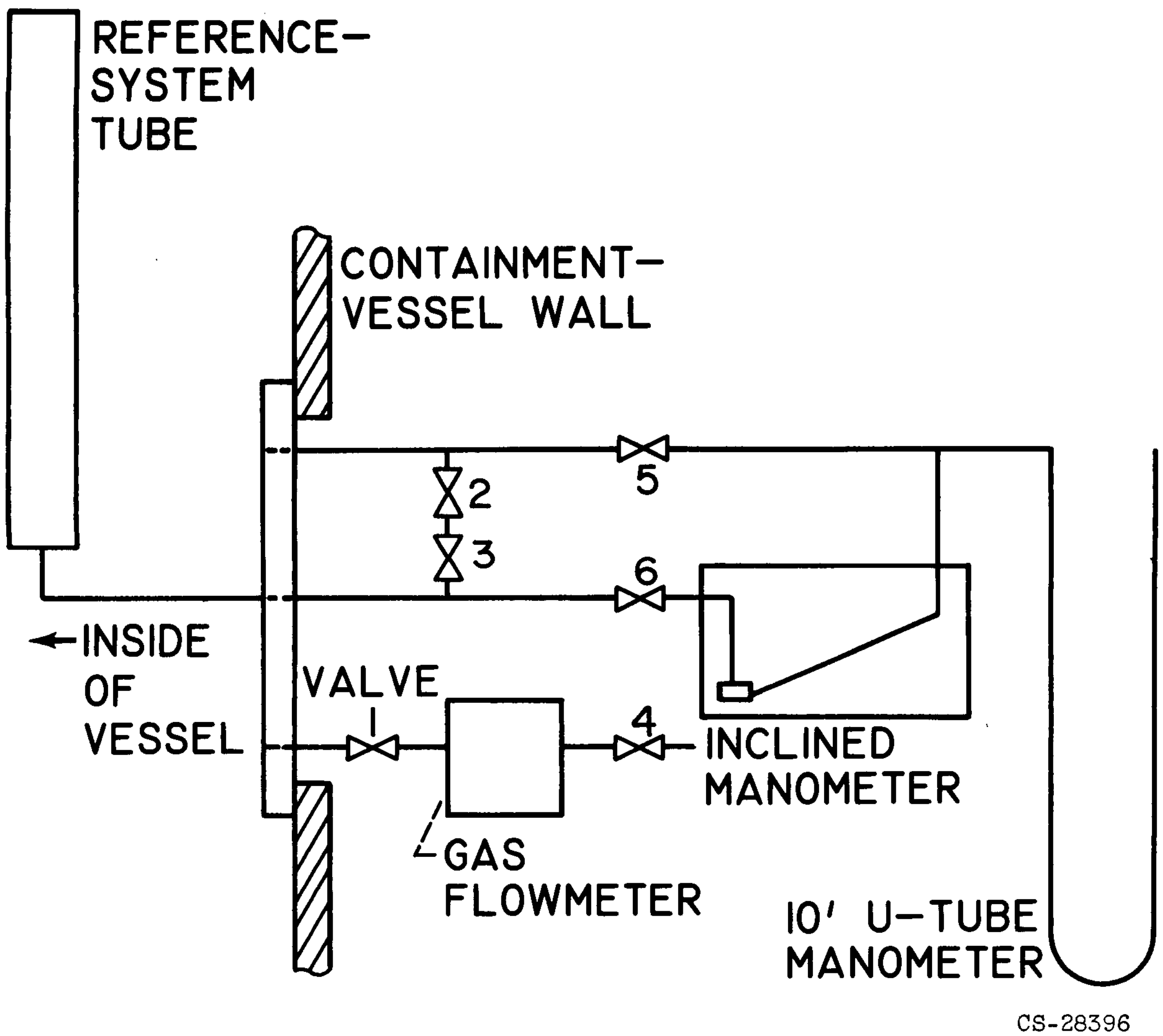

Figure 5. - Schematic of reference system.

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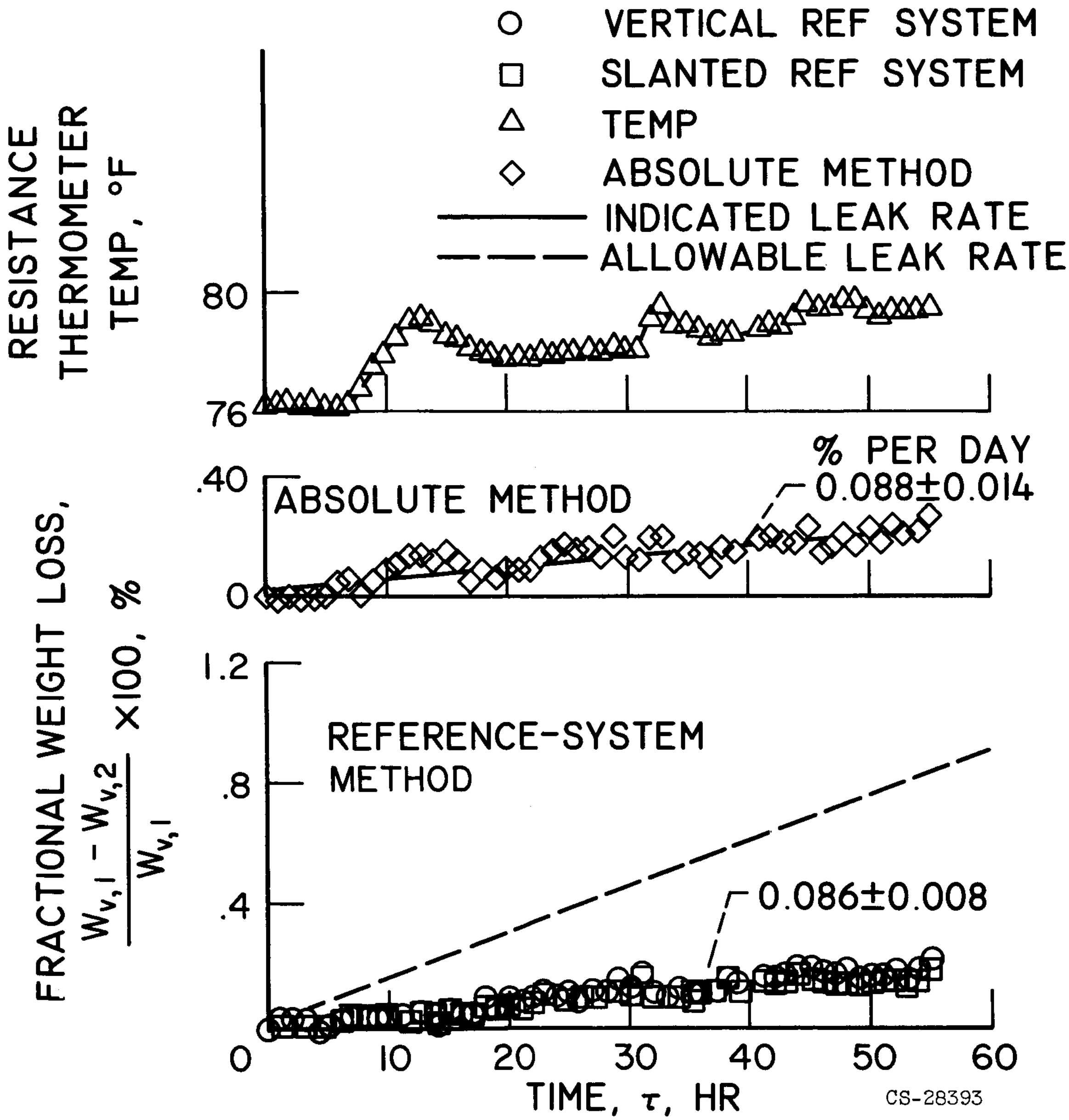

Figure 6. - Leak-rate test 1.

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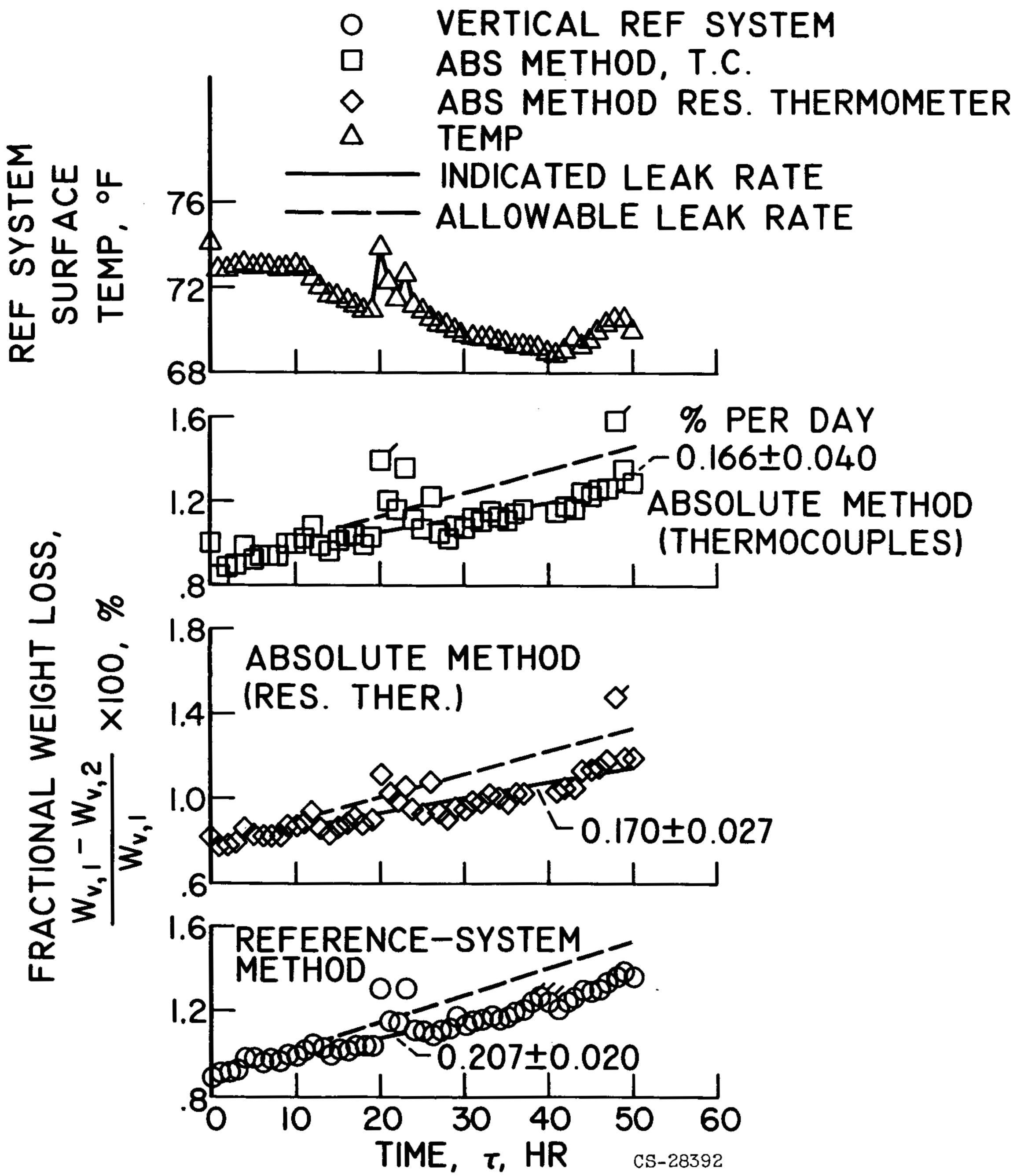

Figure 7. - Leak-rate test 2.

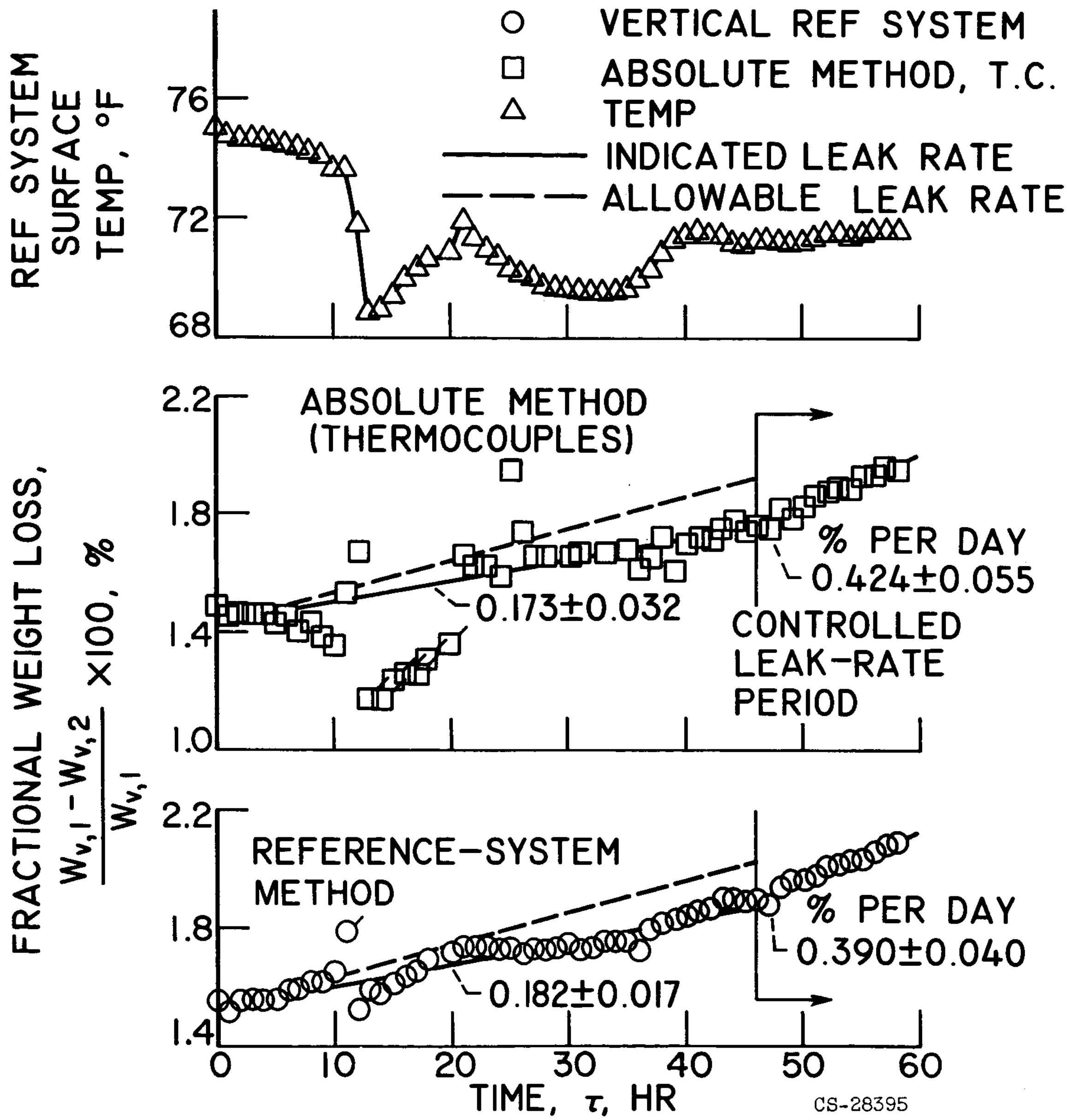

Figure 8. - Leak-rate test 3.